(54) Title: ELECTROSPRAY EMITTER COATED WITH MATERIAL OF LOW SURFACE ENERGY
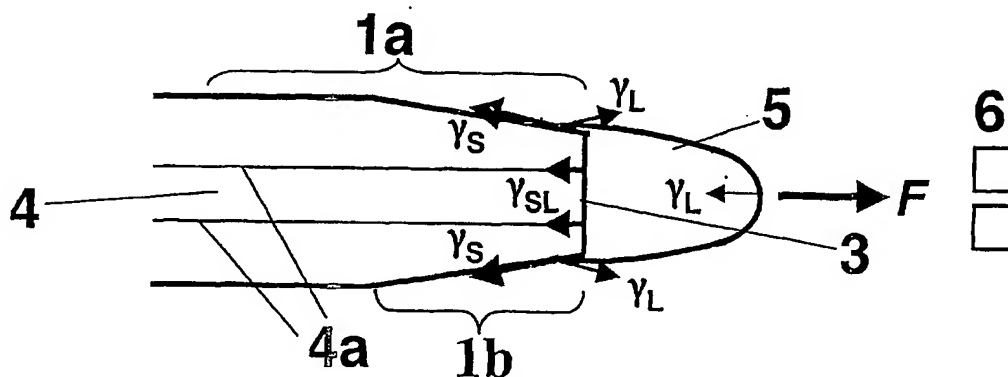
(57) Abstract: This invention relates to an electrospray emitter which comprises an emitter body comprising an inlet orifice, an outlet orifice and a channel connecting the inlet orifice and the outlet orifice; and a coating formed at least on the outer surface of the exit end of the emitter body with a material of low surface energy. The emitters can produce stable electrospray without the aid of any nebulizing gas in the flow rate range of micro- to nano-liters, depending on the surface tension of solvent including distilled water with a high surface tension. The electrically non-conductive nature of their tips virtually eliminates electrical discharge and allows stable electrospray in the negative ion mode. To prevent loss of analytes during delivery between the emitter and analytical devices, e.g., liquid chromatography, a method of coating the inner surface of the connecting line with chemically inert material of low surface energy is also described.

DESCRIPTION

ELECTROSPRAY EMITTER COATED WITH MATERIAL OF LOW SURFACE ENERGY

FIELD OF THE INVENTION

This invention generally relates to electrospray emitters, methods of preparing such emitters, tubular connectors for connecting electrospray emitters with analytical devices, and use thereof.

BACKGROND ART

Electrospray ionization (ESI) mass spectrometry (MS) is now widely used for analyses of biomolecules, pharmaceutical compounds, synthetic polymers and so on (N. Ceck, et al., Mass Spectrom. Rev. 2001, **20**, 362-387). Great needs to enhanced sensitivity and better connectivity for capillary high-performance liquid chromatography (HPLC), especially in proteomics and metabolomics, have led to ESI operation in the low flow rate range of less than 1 μ l/min. This was achieved using tapered capillary emitters with a very small outlet orifice, usually made of glass and fused silica with or without either metal or conducting-polymer coating, and of stainless steel (D. Gale, et al., Rapid Commun. Mass Spectrom. 1993, **7**, 1017-1021; M. Emmett, et al., J. Am. Soc. Mass Spectrom. 1994, **5**, 605-613; G. Valaskovic, et al., Anal. Chem. 1995, **67**, 3802-3805; M. Wilm, et al., Anal. Chem. 1996, **68**, 1-8; E. Maziarz III, et al., J. Am. Soc. Mass Spectrom. 2000, **11**, 659-663; and Y. Ishihama, et al., Rapid Commun. Mass Spectrom. 2002, **16**, 913-918). Practice with these emitters have, however, revealed problems, such as, easy clogging at their exit orifices, and instability of spraying water-rich solution of a high surface tension at an early stage of gradient elution on reverse-phase HPLC being frequently used for proteomics and metabolomics.

These problems are mutually related and arise primarily from the high surface energy (γ_L and γ_S, respectively) of both aqueous solutions and materials the emitters are made of. Electrospray initiates from expansion of liquid into a

dynamic cone with the charged surface (Taylor cone) at the capillary exit by the applied high electric field (for review ref. 1 and references cited therein). When the force of the applied field on and Coulombic repulsion of the surface charges surpass the surface tension of solution, droplets with excess charge of a given sign detach from the cone. Higher surface energy of the tip material (γ_s =about 100 mN/m for glass) produces a cone supported by the base of a larger diameter on the outer wall of the tip (Fig. 1A), leading to a lower charge density on the cone surface, because the rate of excess charge production at the electric contact site of the emitter is rather constant. This causes difficulty in spraying aqueous solutions of the high surface tension (γ_L=73 mN/m), and eventually a need to extremely sharp emitter tips.

DISCLOSURE OF THE INVENTION

In view of the above circumstances, the inventor made intensive studies, and found that these problems can be circumvented by coating at least the exit ends of emitters with material of low surface energy.

Accordingly, the present invention provides an electrospray emitter which comprises an emitter body comprising an inlet orifice, an outlet orifice and a channel connecting the inlet orifice and the outlet orifice; and a coating formed at least on the outer surface of the exit end of the emitter body with a material of low surface energy. Suitable materials of low surface energy include, for example, a fluoropolymer such as perfluoropolyoxetane (hereafter referred to as "PFPO"). The emitter body may be made of fused-silica, glass ceramics, aluminosilicate glass, polypropyrene, or stainless steel. The emitter body is preferably tapered toward the outlet orifice. The inner wall of the emitter body may also be coated with the material of low surface energy.

Another aspect of the present invention relates to a method for making an electrospray emitter, which comprises: providing an electrospray emitter comprising an emitter body having an inlet orifice, an outlet orifice and a channel connecting the inlet orifice and the outlet orifice; and forming a coating with a material of low surface energy at least on the outer surface of the exit end of the emitter body.

According to the present invention, the emitters can produce stable

electrospray of solutions with a variety of surface tensions including distilled water of a high surface tension without the aid of any nebulizing gas in the flow rate range of micro- to nano-liters. The electrically non-conductive nature of their tips virtually eliminates electrical discharge and allows stable electrospray in the negative

5   ion mode. Further, the electrospray emitter of the present invention can show remarkably improved durability because (1) the exit tip can be made broader as compared with conventional emitters because of improved spray efficiency; and (2) non-specific adhesion can be prevented by inner coating of the emitter body. Therefore, the electrospray emitter of the present invention can be made extremely

10   durable, and thus can be used for 500 hours or more.

To prevent loss of analytes in tubular connectors or channels for connecting between the emitter and analytical devices (e.g., liquid chromatography, capillary electrophoresis, supercritical fluid chromatography, and microfabricated channels on a microfluidic device), the inner wall of the tubular connector is coated with a

15   material of low surface energy.

Accordingly, yet another aspect of the present invention relates to a tubular connector for connecting an electrospray emitter and an analytical device, which comprises a tubular connector body comprising an inlet orifice, an outlet orifice and a passage communicating between the inlet orifice and the outlet orifice; and a

20   coating formed on at least a portion of the inner surface of the connector body with a material with low surface energy. Preferably, the inner surface of the connector body is entirely coated with a material with low surface energy. Suitable materials with low surface energy are as described above. The use of the tubular connector of the present invention can improve the recovery of hydrophobic analytes.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A shows the effect of the surface tension of emitter body on the size of a droplet formed at the emitter outlet. Fig. 1B shows the cross-sectional view in the longitudinal direction of the electrospray emitter of one of the embodiments of the

30   present invention. Fig. 1C shows the cross-sectional view of the electrospray emitter at Line C—C of Fig. 1B (1: the emitter body (capillary); 1a: a

polyimide-peeled portion of the exit end that are coated with PFPO; 1b: the tapered

region of the exit end; 2: the inlet orifice; 3: the outlet orifice; 4: the channel

connecting 2 and 3; 4a: the wall of 4; 5: a pre-Taylor cone drip at the emitter exit tip;

6: the counter electrode; F: electric force applied)   In Fig. 1A, the symbol γ denotes

5   the surface tension, and the subscripts S, L, and SL the fused silica/air, water/air, and

fused silica/water interfaces, respectively.

Figs. 1D, 1E and 1F show photographs of fused silica capillary emitters with

the tapered tip coated with PFPO.   (1D: treated with HF, 5 cm in length, and 20-μ

m inner and 150-μ m outer diameters, and the inset shows a magnified view of its

10   tip; 1E: HF-treated. 5 cm in length, and 20-μ m inner and 360-μ m outer diameters;

1F: a pulled capillary of 5.2 cm in length, and 50-μ m inner and 360-μ m outer

diameters.)   The inner diameter of the outlet orifice 3 is 15 μ m (New Objective,

MT).   Its internal coating was limited around the tip, although full internal coating

of 15-μ m ID capillaries with no internal taper was possible.

15   Fig. 2A shows contact angles of the surface of the emitter tips coated with

the indicated concentrations of PFPO.   The ordinate indicates the ratio of the

contact angles of a PFPO-coated to an uncoated tip.   Fig. 2B shows photographs of

water droplets on capillary tips coated with 0.001% and 0.01% PFPO, compared

with those on a non-coated tip.

20   Fig. 3 shows performance of PFPO-coated emitters with distilled water

(3A: Stability of spraying distilled water from a PFPO-coated emitter; and 3B: Rapid

onset of electrospray from distilled water, a high surface tension solvent).   The total

ion current traces (m/z = 150 - 2000) from 6 experiments using the indicated time

lags between starting a pump and a high voltage applied to the emitter are

25   superimposed.

Fig. 4 shows MS analyses of tryptic peptides of reduced and alkylated

bovine serum albumin (0.1 pmol).   An etched, PFPO-coated emitter of 20 μ m

ID/150 μ m OD was used.   (4A: A TIC chromatogram in the positive ion mode.

Experimental conditions are described in the text.;   4B: A full-scan MS spectrum of

30   peptides included in a peak eluted at the retention time of 11.3 min indicated by an

asterisk.;   4C: A full-scan MS/MS spectra of $[M+2H]^{2+}$ ions of m/z 653.5.   A

nominal collision energy was 35%.; and 4D and E: A comparison of base peak chromatograms obtained with internally POPF-coated and uncoated capillaries that connect an injector and a column inlet, respectively.)

Fig. 5 shows positive ion mass spectra of cytochrome c (1 μM) in distilled water containing the indicated additives. The spectra were accumulated for 20 scans. An etched, PFPO-coated emitter of 20 μm ID/150 μm OD was used.

Fig. 6 shows positive and negative ion mass spectra of angiotensin II and ceramides (0.1 μM each). Angiotensin II (6A and B) and ceramide mixtures containing N-Lignoceroyl-4- sphingenine, N-lignoceroyl-sphinganine, and N-stearoyl-4-hydroxy-sphinganine (6C and D). Experimental setups are described in the text. Ceramide spectra were acquired in the alternate positive and negative ion mode.

Fig. 7 shows HPLC/ESI MS of phosphatidylcholine in murine lung lavage in the alternate positive and negative ion mode. (7A: mass chromatograms of $[M+H]^+$ and $[M+HCOO]^-$ ions of DPPC at m/z 734.4 and 778.5, respectively; and 7B and C: positive and negative ion mass spectra of lung lavage phosphatidylcholines eluted around the retention time of 46.8 min. Negative ions were ionized as formate adducts with 46-mass unit larger than the corresponding $[M-H]^-$ ions.)

Fig. 8 shows analysis of prostaglandins by capillary HPLC/ion-trap MS in the negative-ion modes using aqueous acetonitrile. An etched, PFPO-coated emitter of 20-μm ID and 150-μm OD and an ESI voltage of 1.7 kV were used. The HPLC system used was the same as in Fig. 4. The capillary that connect an injector and a column inlet are internally coated with POPF. An 1-μl aliquot of mixtures of PGD_2, PGJ_2, and 15-deoxy-$\Delta^{12, 14}$-PGJ_2 (0.5 pmol each) was gently drawn into a microsyringe containing 10-μl solvent A, and then injected onto a trap column (0.3 × 5 mm) fitted to a 10-port Valco valve. The column was pre-equilibrated with 15% solvent B and developed with a linear concentration gradient of solvent B from 15 to 30 in 1 min and from 30 to 45% in 20 min at the flow rate of ~1.5 μl/min.. 8A: base peak chromatogram (m/z 200-450); Full scan MS spectra for 8B: PGD_2; 8C: PGJ_2; and 8D: 15-deoxy-$\Delta^{12, 14}$-PGJ_2.

Figs. 9A- C show on-line MS^2 product ion spectra of PGD_2, PGJ_2, and

15-deoxy-$\Delta^{12,\,14}$-PGJ$_2$, respectively. Fig. 9D shows MS^3 and MS^4 product ion spectra of 15-deoxy-$\Delta^{12,\,14}$-PGJ$_2$ and PGD$_2$, respectively: the m/z 271 ions in 9C were fragmented on MS^3 scans (upper), and for MS^4 scans of PGD$_2$ carboxylate anions the m/z 351, 315, and 217 ions were sequentially selected (lower). For MS^2, MS^3, and MS^4 scans, relative collision energies of 32-40% were used.

BEST MODE FOR CARRYING OUT THE INVENTION

The present invention will be described in more detail with reference to the preferred embodiments thereof.   However, the following embodiments are representative of the present invention, and are not intended to limit the scope thereof.

(Electrospary Emitters)

Fig. 1B shows one of preferred embodiments of the electrospray emitter of the present invention.   As shown in Fig. 1B, the electrospray emitter comprisies a emitter body 1 comprising an inlet orifice 2, an outlet orifice 3 and a channel 4 connecting the inlet orifice 2 and the outlet orifice 3.   In the present invention coating of the outer surface of the exit end with a material of low surface energy is essential for efficient electrospraying.   Accordingly, in the emitter as shown in Fig. 1B, the coating is formed on the outer surface 1a of the exit tip, preferably on the outer surface 1b.

In the present invention, in addition to the outer surface of the exit tip, the remaining surface of the emitter body may be coated with a material with low surface energy.   In addition to the coating at the exit tip, the inner surface 4a of the channel 4 may be coated with a material of low surface energy at least partly at the outlet end. In a preferred embodiment, the coating can be formed on the entire inner surface 4a of the channel 4.   For example, in the emitters as shown in Figs. 1D and 1E, the PFPO coating is formed on the entire inner surface 4a of the channel 4 in addition to the coating formed on the outer surface 1b.   In the emitter as shown in Fig. 1F, the PFPO coating is formed on the outer surface 1b and on limited areas of the inner surface at the exit end.   However, in these figures, the PFPO coating cannot be seen because of its colorlessness and transparency.

As used herein, the term "low surface energy" means, for example, an energy content of a solid surface (equivalent to the surface tension of a liquid) of not more than 20 mN/m, preferably 5 to 20 mN/m, more preferably 6 to 12 mN/m. The materials with low surface energy, which can be used in the present invention,

5   are not specifically limited as far as they have suitable low surface energy, and can be coated on the emitter body without impairing the performance of the electrospray emitter.   Suitable materials with low surface energy include, for example, a fluoropolymer and fluorinated compound.   Suitable fluoropolymer and fluorinated compound may be selected from perfluoropolyoxetane, perfluorourethane,

10   fluoropolymer elastomers, polytetrafluoroethylene, fluoroalkyl monosilane, polymeric perfluoroether di- and poly-silane, and perfluorooctal and perfluoropolyether with an epoxy, hydroxy, acrylate or isocyanate functional group. Most preferred is perfluoropolyoxetane (PFPO).   PFPO usually has a critical surface tension of 12 mN/m at room temperature.

15   The emitter bodies can be made of fused-silica capillary, but of any material suitable for electrospray emitters including, without limitation, glasses, glass ceramics, aluminosilicate glasses, polypropyrene, and stainless steel. The PFPO coating enabled the capillary of blunt end in the absence of polyimide coating to spray water.

20   Tapered capillary tip is preferred to ensure stable spraying and increased detection sensitivity on MS (refer to, for example, D. Gale, et al., Rapid Commun. Mass Spectrom. 1993, 7, 1017-1021;   M. Emmett, et al., J. Am. Soc. Mass Spectrom. 1994, 5, 605-613;   G. Valaskovic, et al., Anal. Chem. 1995, 67, 3802-3805; and M. Wilm, et al, Anal. Chem. 1996, 68, 1-8).   Accordingly, as

25   shown in Fig. 1B, the emitter body 1 is tapered externally toward the outlet orifice 3. For ESI operation at the flow rate of greater than about 0.1 μl/min, which are used for conventional capillary HPLC, this configuration of the emitter body 1 is practical to avoid clogging at the emitter exit. For ESI operation, such as nanospraying, at further lower flow rate, the outer and inner walls of the emitter body 1 are more

30   preferably tapered toward the outlet orifice 3.   In this case, the emitters with a blunt end should be able to spray water with efficiency lower than those with a tapered

end.

Pulling capillaries, using a commercially available pulling device, can produce their tapered ends (M. Wilm, et al., Anal. Chem. 1996, **68**, 1-8). These pulled capillaries can also be purchased from commercial sources, such as New Objective (Cambridge, MT). Pulling capillary let both inner and outer diameters narrower. Alternatively, the tapered tip of emitters can be produced by hydrofluoric acid (HF) treatment (D. Gale, et al., Rapid Commun. Mass Spectrom. 1993, **7**, 1017-1021). Polyimide coating (if any) was burned off by an appropriate length, e.g., 7 mm, from one end of a capillary of desired length, typically 3-5 cm, and then dipped into a HF solution (46% in the following examples) with gentle stirring for suitable times, depending on the outer and inner diameters of capillaries, e.g., for 20 min for a capillary of 20 μ m inner (ID) and 150 μ m outer (OD) diameters. During the treatment a droplet of HF solution grew larger near a junction between polyimide coating and fused silica surface; the droplet was occasionally blew off by nitrogen flow. In contrast to pulling methods, HF treatment can keep the inner diameter of capillaries at the tip intact, which is important to reduce the risk of particle clogging, especially on high-throughput work. To ensure this during HF treatment, a fluid, preferably water, was pumped through a capillary at a flow rate suitable for its inner diameter, for example, at 200 nl/min for capillaries of 20 μ m diameters. A gas, such as air or a non-reactive gas, preferably nitrogen, is also usable for this purpose. Then the lumen of capillary was flushed and dried by nitrogen gas flow and further dried at 40°C.

The size of the emitter body (such as length, inner diameter and outer diameter) is not specifically limited, and can be designed by a skilled person in the art depending on the application thereof. However, typical emitter body may have a length of 30 to 50 mm. The outer diameter and the inner diameter of the outlet orifice of the emitter are not specifically limited. However, the outer diameter and the inner diameter may range from 150 to 375 and from 10 to 50, respectively. In addition, suitable emitter bodies can be purchased from various commercial suppliers, such as New Objective (Cambridge, Mass.).

(Method of Making Electrospray Emitter)

As mentioned above, another aspect of the present invention provides a method for making an electrospray emitter. Such a method comprises: providing an electrospray emitter comprising an emitter body having an inlet orifice, an outlet orifice and a channel connecting the inlet orifice and the outlet orifice; and forming a coating with a material of low surface energy at least on the outer surface of the exit end of the emitter body. In one embodiment, application of the coating can be carried out, for example, by dipping the portion of the emitter body into a solution of the material with low surface energy in a suitable solvent. After dipping, the solvent is allowed to evaporate, and then leaving the coating on the portion of the emitter body dipped in to the solution.

More specifically, the electrospray emitter of the present invention can be prepared in the following manner. For PFPO coating of capillaries (emitter body) etched by the method described above or of pulled capillaries purchased from New Objectives, the polyimide-peeled tips or non-coated tips were immersed in an appropriate concentration (e.g., from 0.1 to 0.001 wt.% of PFPO) of PFPO in perfluorohexane for from about 1 min. to 10 minutes. Capillaries of any dimensions can be coated, but for capillary HPLC the ones of 10-50 μm in inner diameter (ID) are preferable to avoid clogging during HPLC operation. In etched capillaries of 5 cm in length with intact lumen of 10-50 μm in diameter, simply immersing them in PFPO solutions can coat both the entire length of capillary lumen and outer silica surface, while coating of luminal surface of pulled capillaries with a smaller-bore exit was only limited in their tips. PFPO solutions will be pumped through the capillaries, if necessary, to coat their whole inner surface. After dipping the tips at higher concentrations of PFPO, such as 0.1%, flushing the lumen by air or a non-reactive gas, such as nitrogen was preferable to avoid clogging at the tip orifice, but not always needed. PFPO-treated capillaries stand for at 60°C for 60 min, and then usable for ESI/MS experiments. The thickness of the coating is about 10 nm for coating with 0.1% PFPO. Some examples of the emitter of the present invention are shown in Figs. 1B-F. The PFPO coatings are colorless and transparent, which makes the solvent flow in the emitter tip visible.

Figures 2A and 2B show the dependence of the contact angles of water on emitter tip surface on PFPO concentrations. The ratio of the contact angles of a PFPO-coated to an uncoated tip increased with an increase in PFPO concentration, leveled off around 0.01%, and reached a maximal value of about 2.08 (corresponding

5   to the contact angle of about 122°). PFPO concentrations were preferably less than 0.1% to avoid clogging with the coating material during a drying process, and the optimal concentrations for effective spraying depended on the inner and outer orifice diameters.

(Tubular Connectors For Connecting Emitters with Analytical Devices)

10   The present invention also provides a tubular connector (capillary, tubing, connecting line) for connecting an electrospray emitter and an analytical device, which can prevent sample losses. Such tubular connector comprises a tubular connector body comprising an inlet orifice, an outlet orifice and a passage communicating between the inlet orifice and the outlet orifice; and a coating formed

15   on at least a portion of the inner surface of the connector body with a material with low surface energy. Preferably, the inner surface of the connector body is entirely coated with a material with low surface energy. Suitable materials of low surface energy include, for example, a fluoropolymer and a fluorinated compound. Preferred fluoropolymers and fluorinated compounds are as already described.

20   Most preferred is perfluoropolyoxetane. The tubular connector body may be made of any conventional materials such as fused-silica.

The coating can be formed on the inner surface of the connector body by the method as described above, e.g., a method comprising pumping an appropriate solution containing a material with low surface energy through a channel in the

25   connector body. The person skilled in the art can choose the size of the connector (e.g., length, inner and outer diameter) in accordance with the technical knowledge in this field. Use of the connector as described can prevent loss of analytes during delivery between the emitter and analytical devices, e.g., liquid chromatography.

Hereinafter the present invention is described in more detail with reference

30   to EXAMPLES, but is not deemed to limit the scope of the present invention thereto.

EXAMPLES

EXAMPLE 1 (Preparation of capillaries with the internal surface coated with PFPO)

Fused-silica capillaries with a polyimide coating are now a standard tubing

5   system for capillary HPLC, and it is well known that their inner surface has a

capacity for binding charged and/or hydrophobic analytes, leading to a significant

loss during their delivery in an HPLC tubing system. To prevent those sample

losses, the internal surface of fused-silica capillaries was coated with PFPO. An

appropriate concentration of PFPO (0.1 – 0.001%, more preferably 0.005-0.02%)

10   was pumped through a capillary. It was flushed by a nitrogen flow, and incubated for

60 min at 60°C and then overnight at 40°C.

EXAMPLE 2 (Performance of the emitter tips with water-rich solvent)

At the initial stage of gradient elution on reverse-phase HPLC being

15   frequently used for high-throughput proteomics and metabolomics, emitters must

electrospray water-rich solution, *e.g.*, 2% acetonitrile and 0.1% formate in water, in

the stable cone-jet mode (Cloupeau, M.; Prunet-Foch, B., J. Electrostat. 1989, **22**,

135-159.) immediately after a high voltage is applied. To test whether the emitters

of this invention meet this requirement, their efficiency of spraying distilled water

20   was examined using an etched, PFPO-coated emitter with no internal taper at the tip

by visual inspection and stability of total ion current (TIC) with an ion-trap mass

spectrometer LCQ (ThermoFinnigan, CA). In this and subsequent examples, LCQ

was used for testing performance of the emitters because of its good connectivity for

HPLC, but they can be used with any type of mass spectrometers; fine-tuning of the

25   experimental parameters including dimensions and types of emitter, and MS settings

will be required to obtain an optimal overall performance of an HPLC/MS system,

depending on types of mass spectrometer used. Distilled water was delivered to an

etched, PFPO-coated emitter of 20 μ m ID/150 μ m OD with a syringe pump at the

flow rate of 0.8 μ l/min being suitable for HPLC on a capillary column of 0.1-0.2

30   mm in ID. The counter electrode voltage of 1.8 kV was applied and total ion

current (TIC) of m/z 150-2000 was recorded for 20 min with LCQ; optimal voltages

depended on dimensions of the emitters and the surface tension values of sample solutions, typically in the range of 1.2-2.0 kV. The emitter tip was placed at an appropriate distance, typically about3 mm, in front of a heated capillary inlet of LCQ with a xyz stage (AMR, Tokyo). Using these setups PFPO-coated emitters can stably

5   spray distilled water as shown in Figs. 3A.

It is desirable to keep the high voltage off on washing column between runs, and on injecting sample, otherwise contaminants do enter a mass spectrometer. With the voltage off, droplets in various sizes grows at the tip of emitter, which often prevents conventional, uncoated or metal-coated pulled emitters from spraying after

10   the high voltage is applied again on the next run. To mimic those unfavorable conditions encountered on HPLC/MS, we first started delivering distilled water to a PFPO-coated emitter through a syringe pump and then applied a high voltage after some lag times during which water droplets varying in size form at the emitter tip. All TIC traces of m/z 150-2000 in the positive ion mode from experiments using 6

15   different lag times (0, 0.5, 1, 1.5, 2, and 2.5 min from the onset of charging) shows rapid onset of stable electrospray from distilled water in the cone-jet mode within about 0.15 min (Fig. 3C). These results demonstrate that PFPO-coated emitters are compatible with high-throughput HPLC/MS analyses using an autosampler injection and water-rich solvent for column initialization as well as direct infusion analyses of

20   samples in aqueous solution.

Figures 4A shows a TIC chromatogram of tryptic peptides of 0.1 pmol reduced and alkylated bovine serum albumin on a Magic C18 column (0.2 × 50 mm, Michrom BioResources, Inc.) in the positive ion mode. The column was pre-equilibrated with solvent A (2% acetonitrile and 0.1% formate in water), and

25   developed with a linear concentration gradient of solvent B (90% acetonitrile and 0.1% formate): from 2 to 60% in 20 min at the flow rate of about 1 μ l/min. The total flow rate of Magic2002 pumps (Michrom BioResources, Inc.) was set at 50 μ l/min, and the flow rate across the capillary column was regulated with a Magic variable splitter (Michrom BioResources, Inc.). A 20 μ m ID and 150 μ m OD

30   PFPO-coated emitter was directly connected to an outlet stainless fitting of the column to minimize a peak broadening by diffusion. Input of a contact signal from

HPLC to LCQ started applying an ESI voltage (*e.g.*, 1.7 kV) to the column outlet fitting. Stable electrospray immediately occurred from water-rich solvent A, and last until the end of gradient (Figs. 4A). A full-scan spectrum containing ions of m/z 653 eluting as a base peak (indicated by an asterisk in Fig. 4A) at the retention

5   time of 11.3 min, and its MS/MS spectrum are shown in Figs. 4B and C, respectively. No signal derived from PFPO was observed in the ESI mass spectra over the entire gradient range. The detection sensitivity with the emitters of the present invention was generally similar to that with a metal-coated pulled capillary, but tended to be enhanced for hydrophobic peptides eluting later compared to the latter.

10 PFPO-coated emitters are so robust to be usable for more than 500 hours on reverse phase HPLC/MS of tryptic peptides of proteins separated from crude sources, such as two-dimensional electrophoresis and HPLC.

A base peak chromatogram of tryptic peptides of 0.1 pmol reduced and alkylated bovine serum albumin on a Magic C18 column (0.2 × 50 mm) in Fig. 4D

15 was obtained using a capillary with the internal PFPO coating that connected an autoinjector and a column. Compared with the use of a connecting capillary with no internal coating (Figs. 4E), the use of the former gave good recovery of hydrophobic peptides eluting later.

We next applied the emitters of the present invention to examine the effects

20 of organic solvent concentrations on ESI mass spectra of proteins. The envelopes of peaks of multiply charged positive ions of horse heart cytochrome *c* (1 μM) shifted towards lower m/z values with their maximal intensities at 1766.3, 1374.2, and 883.8 mass units (corresponding to the charges +7, +9, and +14, respectively) with an increase in denaturing power of solvents used: water containing 10 mM

25 ammonium formate (pH 4.2) < water containing 0.1% formic acid (pH 2.73) < 46% acetonitrile containing 0.1% formic acid, respectively. This is consistent with the results of previous studies, and those shifts to lower m/z was attributed to the degrees of exposure of ionizable side chains to solvent by protein conformational changes (S. Chowdhury, et al., J. Am. Chem. Soc. 1990, **112**, 9012-9013.). The emitters of this

30 invention will therefore help study conformations and unfolding/folding of proteins in gas-phase as a function of their conformation in solution including native

conformation in purely aqueous solutions. Moreover, the recent development of ultra-high resolution Fourier transform ion cyclotron resonance MS are drawing much attention to analyses of whole proteins by MS including MS/MS without protease digestion (S. Sze, et al., Proc. Natl. Acad. Sci. USA. 2002, **99**, 1774-1779.).

5   Organic solvents are usually included in sample solutions to assist ESI by conventional emitters, but are prone to cause uncontrollable denaturation and aggregation of proteins. The present emitters compatible with MS analyses in their absence will be helpful in studying whole proteins.

10   **EXAMPLE 3 (Capability of the emitter for negative ion MS)**

There is an increased risk of corona discharge or arcing in the negative ion mode versus in the positive ion mode (Ceck, N. B.; Enke, C. G.,   Mass Spectrom. Rev. 2001, **20**, 362-387).   In particular, conventional metal-coated emitters are prone to experience corona discharge that damages a coated tip.   This prevents a

15   stable spraying of negative ions, thereby hindering their coupling to HPLC or other separation methods that require a stable operation of ESI for a longer time period. Very recently, nanoelectrospray emitters coated with polyaniline, a conductive polymer, was reportedly resistant to electrical discharge and durable for at least an hour in the negative ion mode (P. Bigwarfe, et al., Rapid Commun. Mass Spectrom.

20   2002, **16**, 2266-2272).   The tips of PFPO-coated emitters are electrically non-conductive.   This virtually eliminates electrical discharge and allows stable electrospray in the negative ion mode as well as in the positive ion mode.   This is exemplified by mass spectra of peptides, ceramides, phospholipids, and prostaglandins (PG) as follows.

25   Angiotensin II (0.1 μ M) dissolved in 7 volumes of solvent A and 3 volumes of solvent B was continuously infused through a 20 μ m ID and 150 μ m OD PFPO-coated emitter at the flow rate of 0.4 μ l/min, and the onset of electrospray was initiated with an applied voltage of 1.8 kV. LCQ was separately tuned and spectra were individually acquired for the positive and negative ion scans.

30   Angiotensin II contains an acidic and 2 basic residues with a calculated pI of 7.81, and thus is positively charged in the presence of 0.1% formate (pH 2.73),

unfavorable for the formation of negative ions in solution. The negative ion spectrum, however, exclusively contained abundant, singly charged [M H] ions at m/z 1044.6, compared to the positive ion spectrum with $[M+2H]^{2+}$ ions of m/z 524 predominant (Figs. 6A and B). The signal intensity of a base peak in the positive

5   ion spectrum were 8.4 times that in the negative ion spectrum, but their signal-to-noise (S/N) ratios were similar to each other, consistent with lower levels of chemical noises and contaminant peaks in the negative ion mode. These results indicate a potential importance of applying negative ion MS measurements with PFPO-coated emitters to proteomics studies.

10   Another example using less polar solvent mixtures is a comparison of positive and negative spectra for three ceramide species that were acquired simultaneously by an alternate polarity switching (M. Ito, et al., J. Biol. Chem. 2002, 277, 43674-43681; and Tojo, H.; Japan Patent Publication 2003-028849). N-Lignoceroyl-4-sphingenine   (S),   N-lignoceroyl-sphinganine   (Sa),   and

15   N-stearoyl-4-hydroxy-sphinganine (P), 0.1 μ M each, were dissolved in hexane/2-propanol/ethanol; 5 : 4 : 1 (v/v/v) containing 5 mM ammonium formate. The mixtures were sprayed through a $50\,\mu$ m ID and $150\,\mu$ m OD PFPO-coated emitter at the flow rate of about 2 μ l/min with an applied voltage of 1.4 kV. The low surface tension of the solvent system used and the emitter tips led to stable

20   electrospray in the positive and negative ion modes with the alternate polarity switching controlled by LCQ's Xcalibur software. The signal intensity of a base peak in the positive ion spectrum were about 20 times that in the negative ion spectrum, but the S/N ratio was somewhat better in the latter. $[M+H]^+$ ions of Sa, S, and P at m/z 652.5, 650.3, and 584.4,respectively, and the corresponding [M H]

25   ions with m/z values smaller by 2 mass units were predominantly observed (Figs. 6C and D). A peak of positive ions of m/z 584.4 arose from loss of H_2O from S, characteristic of 4-sphingenine containing ceramides. The solvent system used contained 5 mM formate to enhance ionization efficiency of ceramides, which was prone to form formate adduct ions in the negative ion mode. Applying an in-source

30   low voltage (ca. 20V) prevented forming these adducts, and helped generate structurally informative [M H] ions of ceramides (Fig. 6D).

Mass spectrometry in proteomics handles peptides of more or less similar chemical properties, but metabolomics needs high throughput identification of huge numbers of metabolites with the vast spectrum of hydrophobicities and proton affinities, which in turn ideally need ESI conditions customized to each analyte

5   during chromatography. As the first step for this challenging task, monitoring both positive and negative ions on a single chromatographic run would help in identifying the structures of analytes. This example shows analysis of the major lung surfactant, dipalmitoyl- sn-glycero-3-phosphocholine (DPPC), in murine lung lavage by normal-phase HPLC/ESI-MS in the alternate polarity switching mode. DPPC levels

10   increase in pulmonary alveolar proteinosis (G. Hook, et al., Toxicol. Pathol. 1991, 19, 482-513), but decrease in severe lung diseases including adult respiratory distress syndrome in severe shock (W. Seeger, et al., Lung 1990, 168, 891-902 (Suppl)) and probably rejection after lung transplantation (J. Hohlfeld, et al., Am. J. Respir. Crit. Care Med. 1998, 158, 706-712). Hence, its analysis would be clinically important,

15   such as in critical care management. Normal-phase HPLC on a LichroSphere Si-100 (1×150 mm) was connected to the same emitter as previously used for ceramide analysis (Fig. 6). An aliquot of lipids extracted from right lung lavage by the method reported previously (M. Ito, et al., J. Biol. Chem. 2002, 277, 43674-43681) was injected to the column pre-equilibrated with solvent C,

20   hexane/2-propanol/ethanol (4 : 5 : 1 v/v), at the flow rate of 50 μ l/min, and the column was developed with a linear gradient of solvent D, solvent C/1 M ammonium formate in water/water (100: 2.24: 9.76 v/v/v) from 0 to 100% in 20 min and then holding at 100% for 30 min at the flow rate of 50 μ l/min. The effluent was split with a tee to yield a flow rate across the column of about 1.5 μ l/min, and monitored

25   with a LCQ in either data dependent negative or positive ion MS/MS mode as well as in alternate positive and negative ion full scan mode on a single run. Since DPPC contains a quaternary ammonium ion, ESI generates its abundant [M+H]$^+$ ions, but hardly [M H] ions; the presence of formate ions in elution solvents promoted forming formate adduct ions of phosphatidylcholine (Fig. 7B and C). Mass

30   chromatograms of the [M+H]$^+$ or [M+HCOO] ions of DPPC show a single peak at the retention time of 46. 8 min (Fig. 7A). The signal intensity of [M+H]$^+$ ions of

DPPC (m/z 734) were 24 times that of the corresponding [M+HCOO] ions, but the S/N ratios were comparable. Murine lung lavage mainly contained di-saturated DPPC, but did appreciable amounts of species with an unsaturated acyl group: C16:0/C18:1 (m/z 760), C16:0/C18:2 (m/z 758), C16:0/C22:6 (m/z 806),

5 C16:0:C16:1 (m/z 732), and C16:0/C20:4 (m/z 782) in this decreasing intensity order in the positive ion mode, where $Cn:m$ indicates an acyl group with n carbons and m double bonds in diacyl phosphatidylcholines. The results were consistent with those in the negative ion mode.

10 **EXAMPLE 4**

To further examine the utility of the emitters in the negative ion mode using aqueous solvents, we analyzed the mixtures of prostaglandin D_2 (PGD$_2$) and its bioactive metabolites PGJ$_2$ and 15-deoxy-$\Delta^{12, 14}$-PGJ$_2$ by capillary reverse-phase HPLC on a Magic C$_{18}$ column (50×0.2 mm). The solvent systems used were the

15 same as those for peptide separation as described above, but the column was pre-equilibrated with 15% solvent B and developed with a linear concentration gradient of solvent B from 15 to 30 in 1 min and from 30 to 45% in 20 min at the flow rate of ~1.5 μl/min.   PGJ$_2$ and 15-deoxy-$\Delta^{12, 14}$-PGJ$_2$ are formed from PGD$_2$ by the elimination of one and two water molecules, respectively. Stable electrospray

20 immediately occurred from water-rich, 15% solvent B, and last until the end of gradient (Figs. 8A). Full-scan spectra of these prostaglandins (0.5 pmol each) contain abundant deprotonated ions and minor formate-adduct ions. No signal derived from coating material was observed in the ESI mass spectra over the entire gradient range. The MS^2 product ion spectra of [M H] ions of PGD$_2$ and PGJ$_2$ contain abundant

25 fragment ions generated by losses of one and two water molecules (m/z 333, and 315) and losses of water and hexanal formed by cleavage at the bond between C^{14} and C^{15} (m/z 233) (Figs. 9A and B), consistent with the results of a previous study with fast atom bombardment MS (J. A. Zirrolli, J. Am. Soc. Mass Spectrom., 1, 325-335.). The neutral loss of CO$_2$ from the [M H] ions of 15-deoxy-$\Delta^{12, 14}$-PGJ$_2$

30 yielded abundant m/z 271 ions (J. A. Hankin, Arch. Biochem. Biophys., 340, 317-330) which underwent extensive fragmentation of the charge remote type on

MS^3 scans with m/z 315, and 271 ions isolated sequentially for collision-induced dissociation (Fig. 9C). MS^4 scans gave the similar pattern with m/z 351, 315, and 271 ions isolated sequentially as precursor ions (Fig. 9D), confirming the fragmentation path of the carboxylate anions of PGD$_2$. These results indicate that the use of the

5   emitters of this invention facilitates MS analyses in combination with HPLC and other separation methods in both proteomics and metabolomics.

INDUSTRIAL APPLICABILITY

According to the present invention, the emitters can produce stable

10   electrospray without the aid of any nebulizing gas in the flow rate range of micro- to nano-liters, depending on the surface tension of solvent including distilled water with a high surface tension.   The electrically non-conductive nature of their tips virtually eliminates electrical discharge and allows stable electrospray in the negative ion mode. These characteristics of the emitters are compatible with high-throughput

15   reverse phase HPLC using water-rich solvent in the early phase of gradient elution on proteomics and metabolomics, and studies using intact proteins in purely aqueous solutions. The latter includes protein-protein interaction, protein-ligand interaction, protein conformational changes, and protein folding-unfolding equilibrium. In addition, the present emitters is applicable to MS analyses of whole proteins using

20   ultra-high resolution Fourier transform ion cyclotron resonance MS in the absence of organic solvents that can assist ESI by conventional emitters, but cause protein precipitations. The capability of the emitters of the present invention in the negative ion modes facilitates ESI-MS application to metabolomics (S. Takagi, et al., J. Clin. Invest 2003, 112, 1372-1382) and pharmacological profilings.

25   The present invention also provides a tubular connector (capillary, tubing, connecting line) for connecting an electrospray emitter and an analytical device, which can prevent sample losses. The coating with a material of low surface energy in this invention is applicable to the micro-channels of microfluidic devices as well as the channels of liquid-delivering connectors between analytical devices.

30   The present invention can be practiced based on the above description, however, for reference purposes, the following references are incorporated herein.

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CLAIMS

1. An electrospray emitter which comprises an emitter body comprising an inlet orifice, an outlet orifice and a channel connecting the inlet orifice and the outlet orifice; and a coating formed at least on the outer surface of the exit end of the emitter body with a material of low surface energy.

2. The electrospray emitter according to Claim 1, wherein the material of low surface energy is a fluoropolymer or a fluorinated compound.

3. The electrospray emitter according to Claim 2, wherein the fluoropolymer or the fluorinated compound is selected from perfluoropolyoxetane, perfluorourethane, fluoropolymer elastomers, polytetrafluoroethylene, fluoroalkyl monosilane, polymeric perfluoroether di- and poly-silane, and perfluorooctal and perfluoropolyether with an epoxy, hydroxy, acrylate or isocyanate functional group.

4. The electrospray emitter according to Claim 1, wherein the material of low surface energy is perfluoropolyoxetane.

5. The electrospray emitter according to Claim 1, wherein the coating is transparent or translucent.

6. The electrospray emitter according to Claim 1, wherein the emitter body is made of fused-silica, glass ceramics, aluminosilicate glass, polypropyrene, or stainless steel.

7. The electrospray emitter according to Claim 1, wherein the emitter body is tapered toward the outlet orifice.

8. The electrospray emitter according to Claim 4, wherein the outer wall and the inner wall of the emitter body are tapered toward the outlet orifice.

9. The electrospray emitter according to Claim 1, wherein the inner wall of the emitter body is also coated with the material of low surface energy according to Claim 2.

10. The electrospray emitter according to Claim 1, wherein the outlet orifice has an inner diameter of from 10 to 50 μ m.

11. A method for making an electrospray emitter, which comprises:

providing an electrospray emitter comprising an emitter body having an inlet orifice, an outlet orifice and a channel connecting the inlet orifice and the outlet orifice; and forming a coating with a material of low surface energy at least on the outer surface of the exit end of the emitter body.

5   12.   A tubular connector for connecting an electrospray emitter and an analytical device, which comprises a tubular connector body comprising an inlet orifice, an outlet orifice and a passage communicating between the inlet orifice and the outlet orifice; and a coating formed on at least a portion of the inner surface of the connector body with a material with low surface energy.

10   13.   The tubular connector according to Claim 12, wherein the material of low surface energy is a fluoropolymer or a fluorinated compound.

        14.   The tubular connector according to Claim 13, wherein the fluoropolymer or the fluorinated compound is selected from perfluoropolyoxetane, perfluorourethane, fluoropolymer elastomers, polytetrafluoroethylene, fluoroalkyl

15   monosilane, polymeric perfluoroether di- and poly-silane, and perfluorooctal and perfluoropolyether with an epoxy, hydroxy, acrylate or isocyanate functional group.

        15.   The tubular connector according to Claim 12, wherein the material of low surface energy is perfluoropolyoxetane.
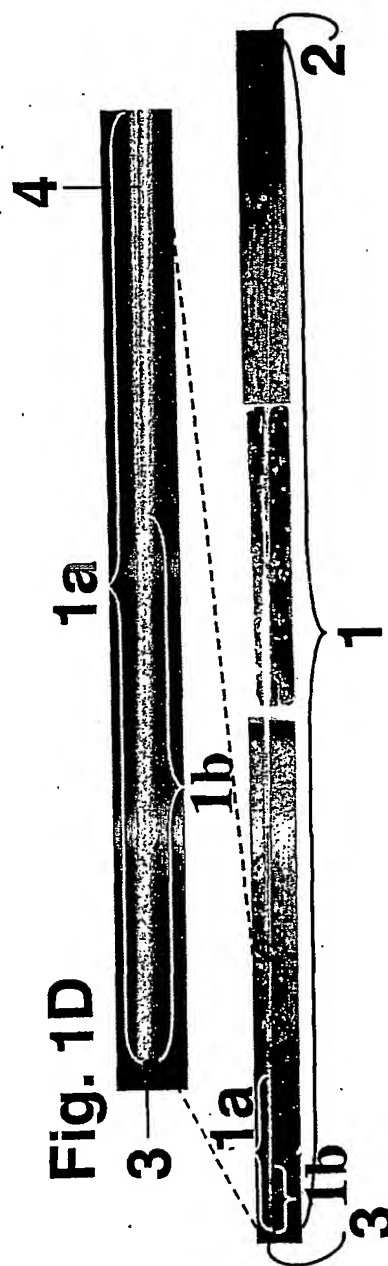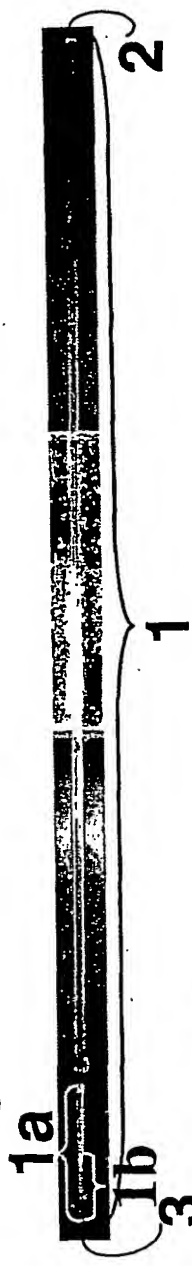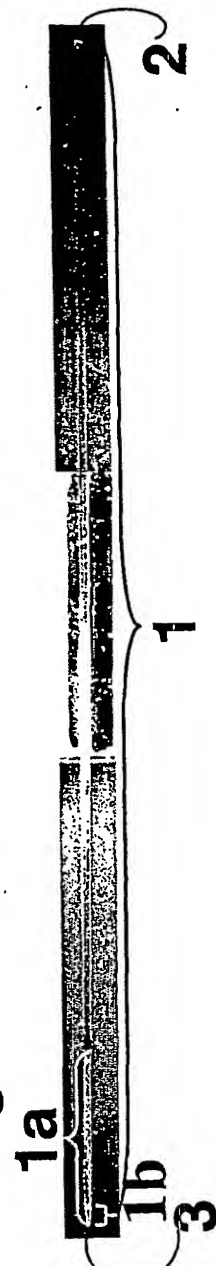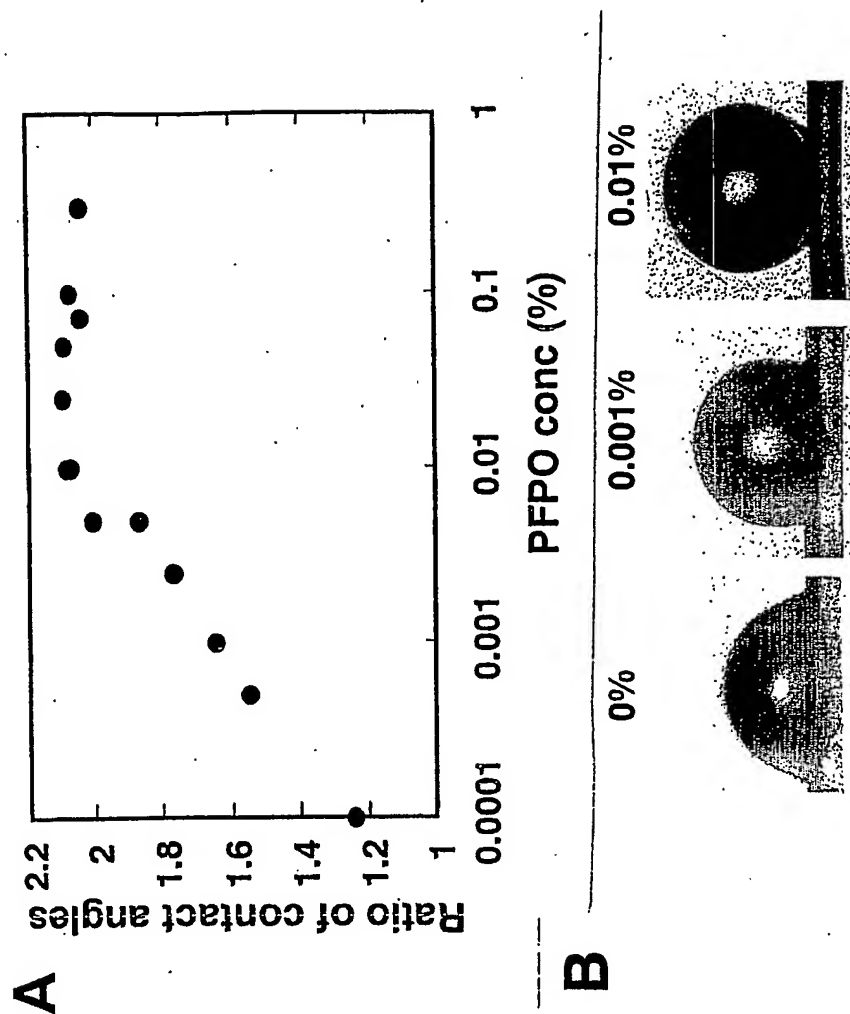
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Fig. 1A

Fig. 1B

Fig. 1C

Fig. 1D

Fig. 1E

Fig. 1F

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9
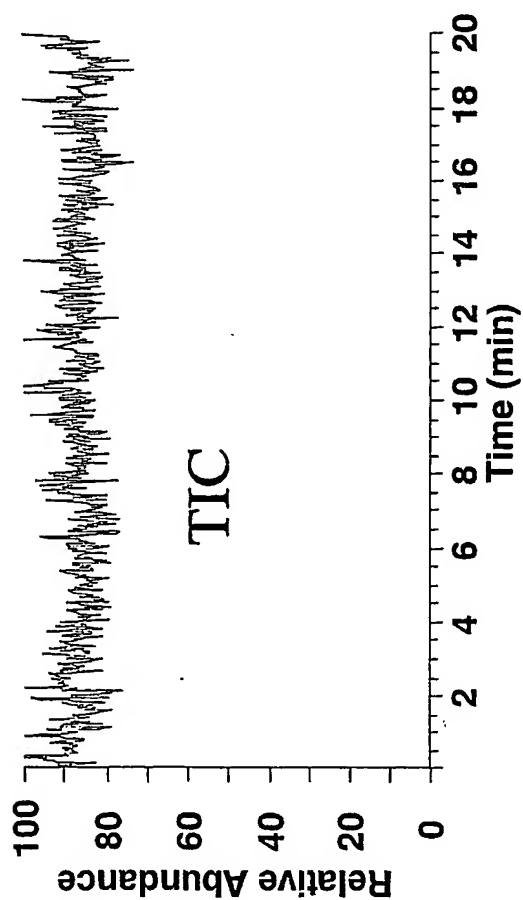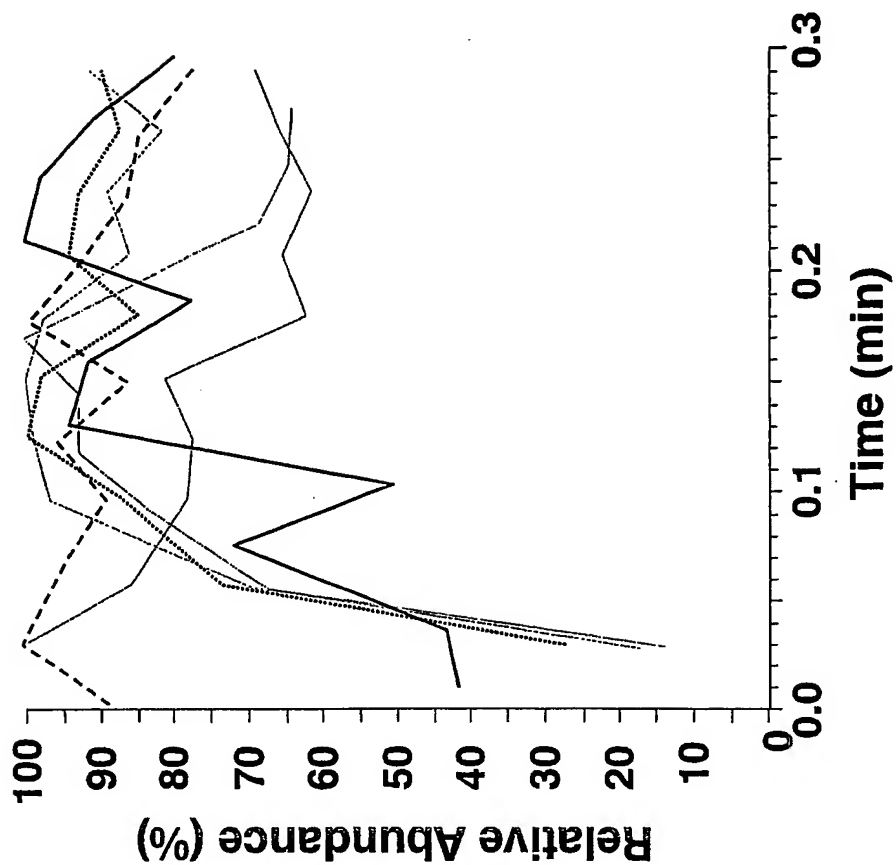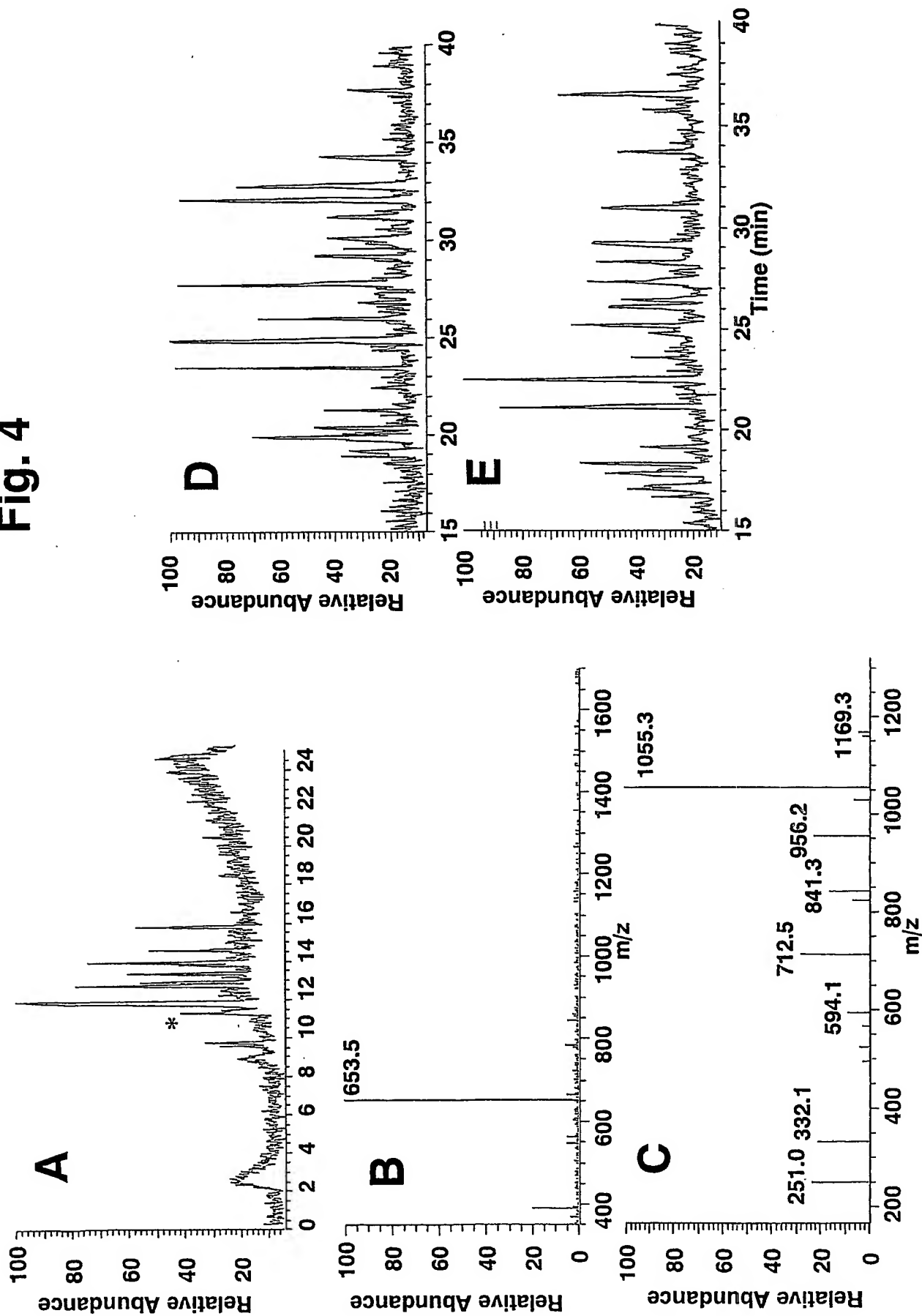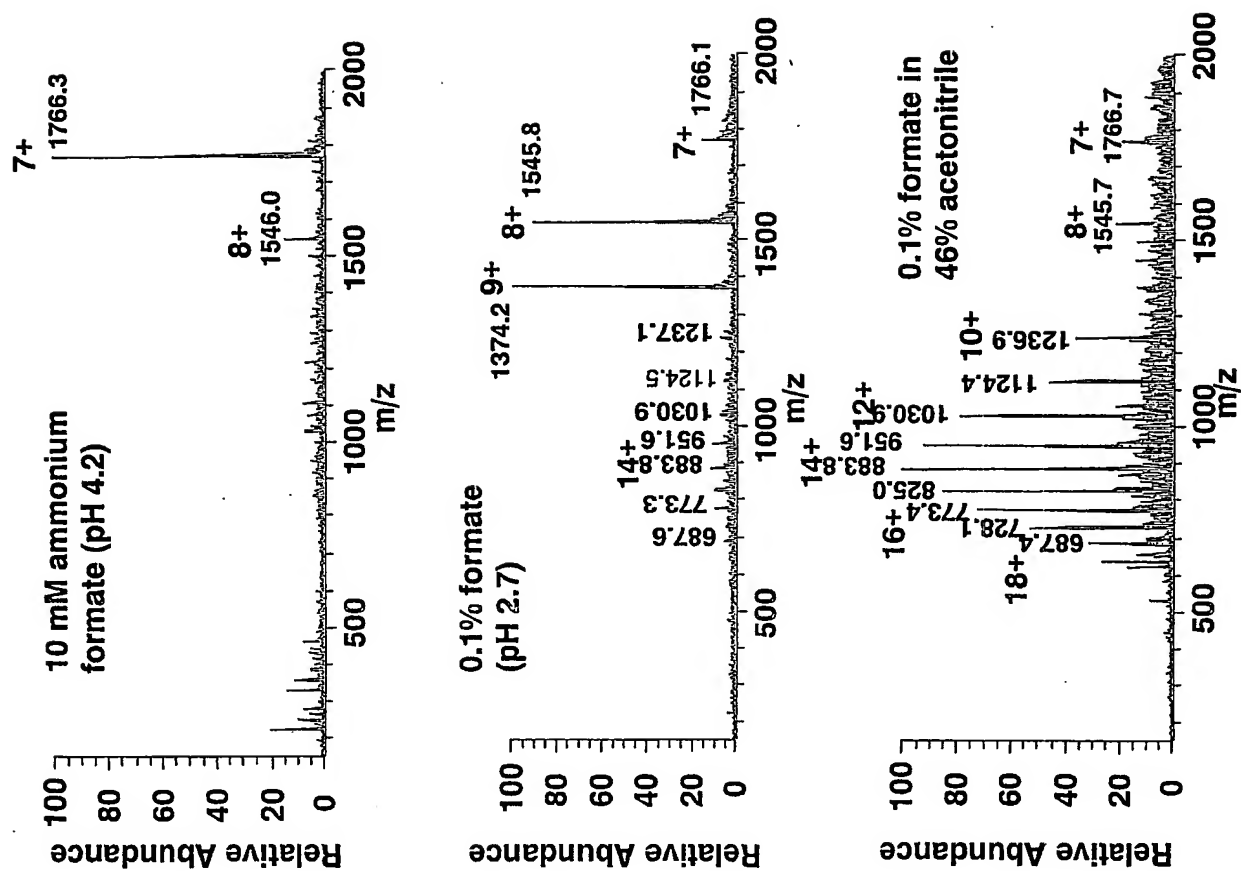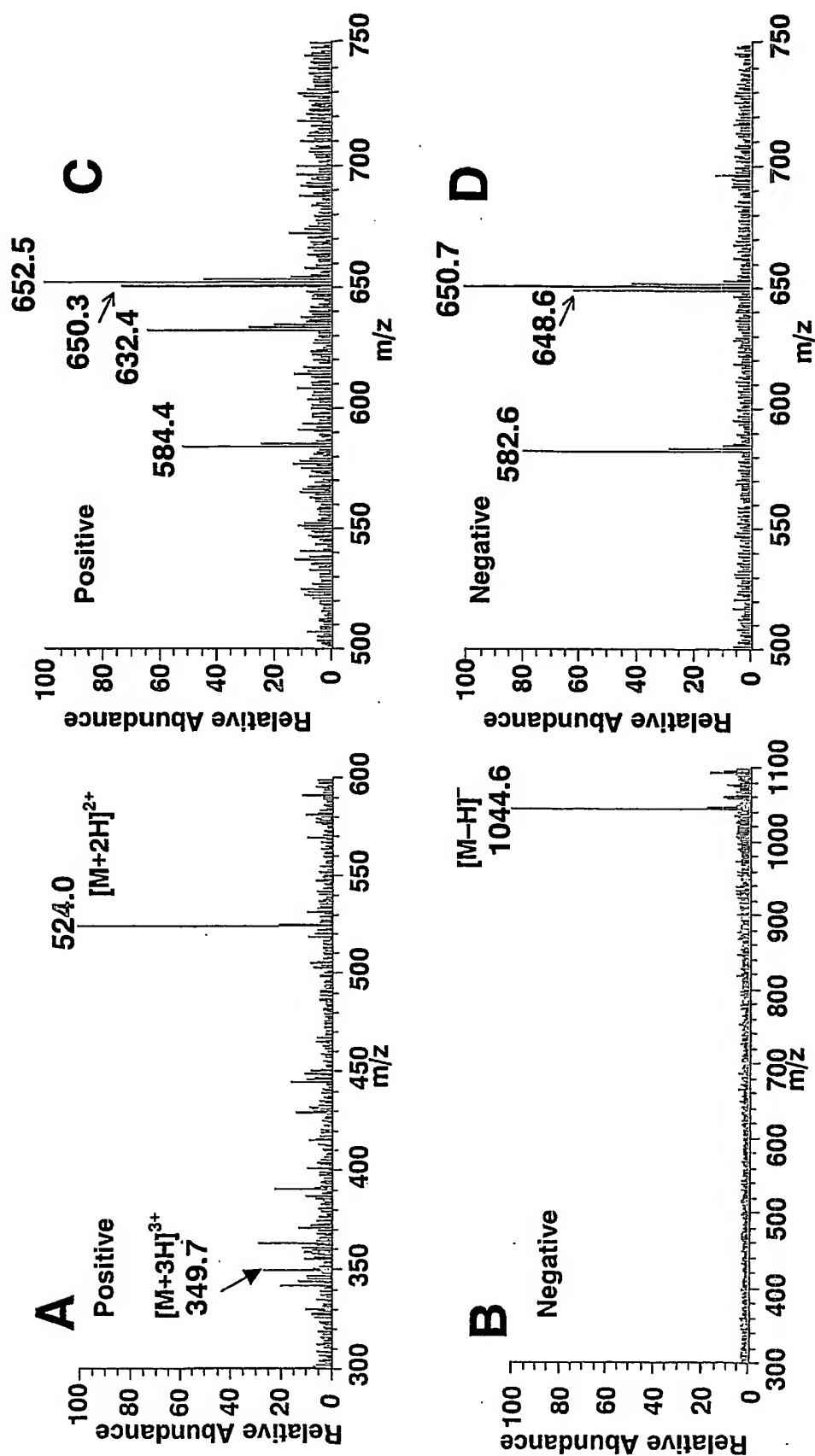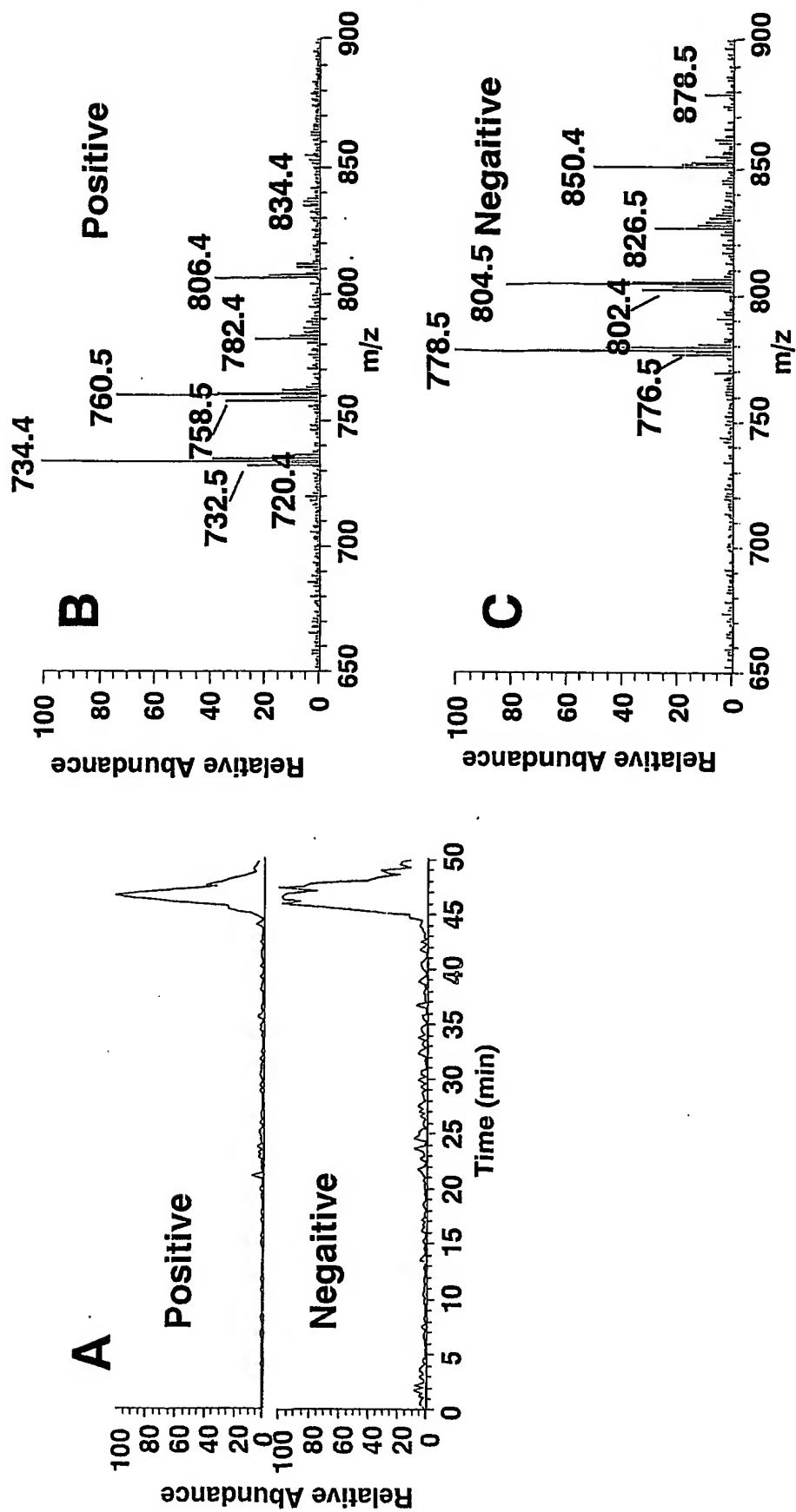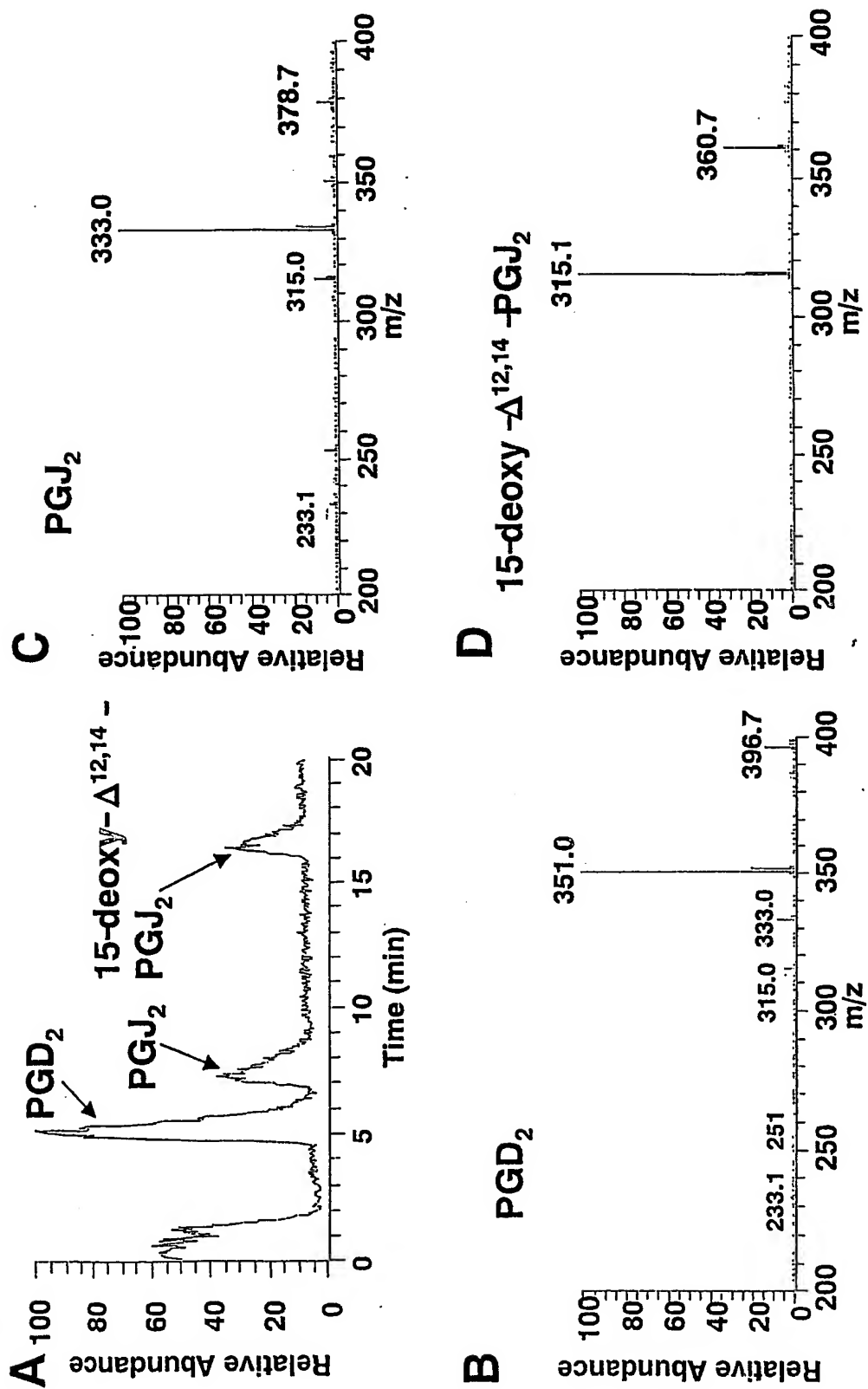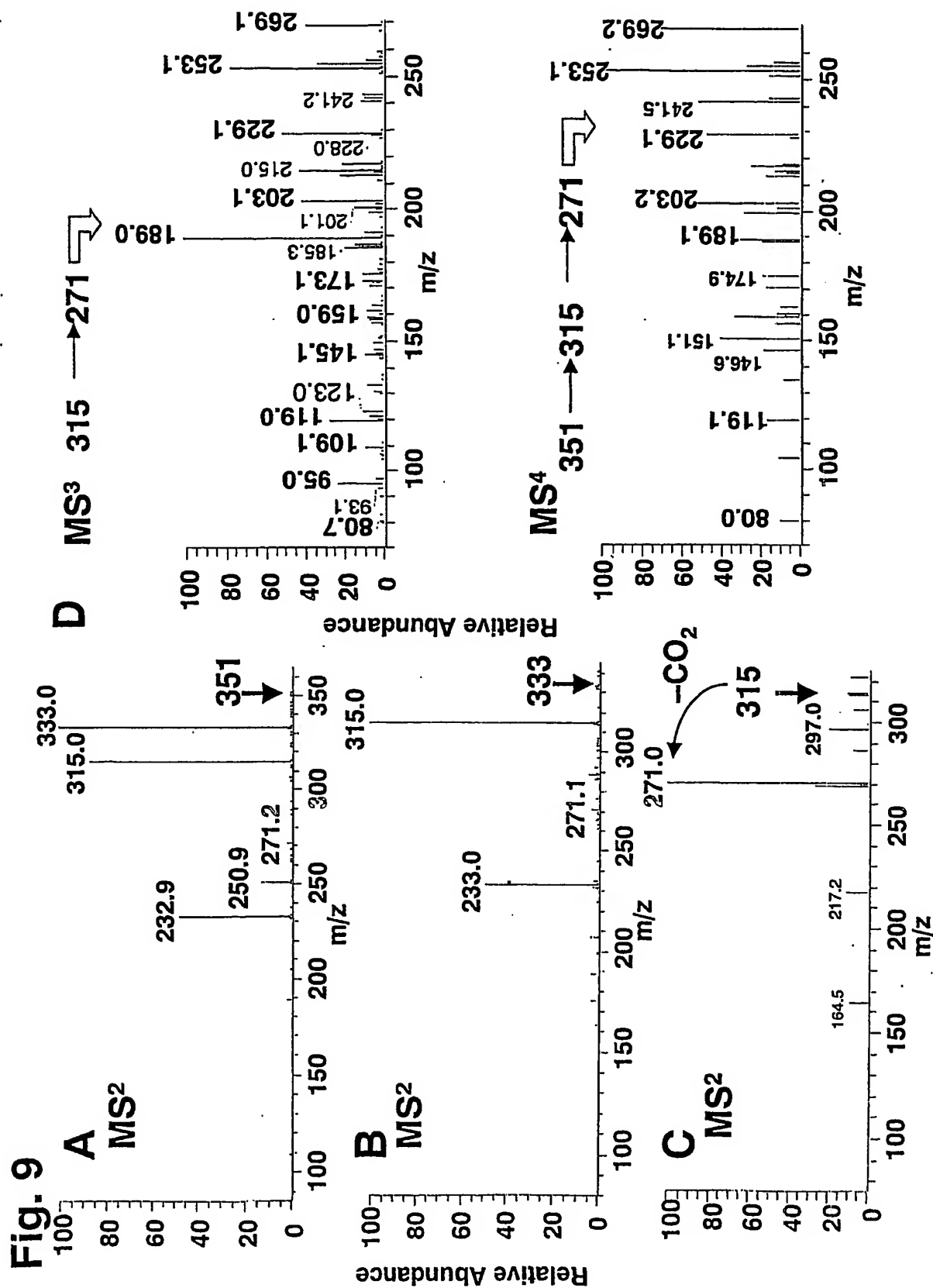
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01N30/72   //H01J49/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G01N   H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO 01/50820 A (UNIV NEW YORK) 12 July 2001 (2001-07-12) abstract page 2, line 32 -page 3, line 6 page 4, line 7 - line 25 page 6, line 13 - line 15 page 6, line 31 page 7, line 26 -page 8, line 5 page 8, line 29 -page 9, line 6 page 9, line 12 - line 17 figure 1A figure 3 ――― -/--	1,5-8, 10,11 2-4

[X]	Further documents are listed in the continuation of box C.	[X]	Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
17 May 2004	26/05/2004

Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Authorized officer Bravin, M

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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